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Visual function before and after the removal of bilateral congenital cataracts in adulthood

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Abstract

Subject Peter Doyle (PD) had congenital bilateral cataracts removed at the age of 43. Pre-operatively PD's visual acuity was 20/80, with a resolution limit around 15 cpd, and he experienced monocular diplopia with high contrast stimuli. Post-operatively PD's visual acuity improved to approximately 20/40, with a resolution limit around 25 cpd. Using a variety of pre- and post-operative tests we have documented a wide range of neural adaptations to his limited and distorted visual input, and have found a limited amount of post-operative adaptation to his newly improved visual input. These results show that the human visual system is capable of significant adaptation to the particular optical input that is experienced.

Keywords: Bilateral congenital cataracts; Recovery of function; Plasticity; Laser interferometry; Stiles–Crawford effect; Contrast constancy

1. Introduction

The first scientific study of sight restoration after removal of long-term bilateral congenital cataracts was reported by Cheselden (1728) 270 years ago. Since then, there have only been a handful of similar cases (Grant, 1709; Gregory & Wallace, 1963; Latta, 1904; Morgan, 1977; Sacks, 1993; Valvo, 1971; von Senden, 1960), as bilateral cataracts are extremely rare (Taylor, 1998), and are almost always noticed and removed by late infancy. We describe here a case study of a co-author, Peter Doyle (PD), who had congenital bilateral cataracts removed when he was 43.

At the time of the last studies attempting to characterize the effects of long-term deprivation on the human visual system little was known about the neural basis of vision, including the neural effects of monocular (Kugelberg, 1992; Vaegan & Taylor, 1979; Wright, Christensen, & Nuguchi, 1992) and binocular visual deprivation (Wiesel & Hubel, 1963, 1965a,b). Earlier studies tended to concentrate on how well patients used their sight functionally, and on the susceptibility to severe depression that often followed surgery (Ackroyd, Humphrey, & Warrington, 1974; Gregory & Wallace, 1963; Sacks, 1993; Valvo, 1971). More subtle visual deficits have tended to go unstudied, and pre- and post-operative measures of performance relied heavily on anecdotal and subjective perceptual observations.

PD's pre-operative vision was significantly better than that of most earlier patients (pre-operative visual acuity of 20/80) and his visual development seemed to be grossly normal: he showed no evidence of nystagmus or deficits in form vision, and functional magnetic resonance imaging revealed no peculiarities in either the structure or the retinotopy of his visual areas. Rather than studying a grossly abnormal visual system, the experiments in this paper address more subtle questions of how the visual system adjusts to limited and distorted visual input. The visual system of normal observers has been shown to be well adapted to their environment (Atick & Redlich, 1990; Barlow, 1961; Olshausen & Field, 1996). However it has remained an open question to what extent this match between visual processing and the environment is due to evolutionary as opposed to developmental factors. It is also unclear to what extent this adaptation is an ongoing process persisting throughout adulthood. The process of neural compensation for PD's optics probably began sometime between

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13 months (when his cataracts were not yet observable) and 21 months (when they were clearly present). At that stage PD's visual system seems to have still been relatively plastic: our paper documents a wide range of neural adaptations resulting from the peculiarities of his visual input. In contrast, PD's post-operative re-adaptation over time has thus far been fairly limited, consistent with animal studies indicating that the visual system is less plastic in adulthood.

The many tests we carried out should facilitate comparisons between PD and any similar patients in the future. Relying on quantitative data as well as qualitative observations demonstrated that PD, both pre- and post-operatively, often noted striking perceptual distortions of his visual input which, when tested psychophysically, were often consequent on relatively small psychophysically measured deficits. It seems that even deficits in visual processing that are relatively subtle when measured psychophysically can dramatically affect the quality of visual experience.

1.1. PD's case history

PD's cataracts were not evident at birth to either his parents or the family doctor. No cataracts were noticed at 13 months, when insect bites caused swellings around PD's forehead and his right eye, suggesting his cataracts were not yet present, or were not yet easily visible. At 21 months PD's mother first noted his cataracts. According to the family doctor, "*Mother noted whiteness in black pupils of each eye. Both parents feel they may have noted this in the past... Pupils dilated with cyclogel... lenticular opacities*; *large*, *not very dense... Cataracts*, *probably congenital*". Although it may seem surprising that it took this long for PD's cataracts to be diagnosed, gradual lens opacification in early infancy is difficult to determine by external visual inspection alone (Rahi & Dezateaux, 1999). PD's cataracts continued to grow denser over time: as an adult PD was described by various doctors as having dense central nuclear opacification.

By the time he was three years old, PD's cataracts were clearly visible, and he was having trouble with steps, street curbs and with recognizing people. His poor vision affected him at play, and when reading he held books very close to his face. PD's doctor took a conservative stance, and rather than removing the cataracts, PD's pupils were dilated with 1% atropine sulfate every three days. Atropine enlarged his pupils beyond the extent of the cataracts, allowing PD to see blurred images of the world 'around the cataracts' through roughly annular pupils (Fig. 1b). A year and a half after the beginning of the atropine treatment his doctor noted that PD (now $4\frac{1}{2}$ years old) was "*doing fine on steps*, *recognition*, *etc.*", was doing well at nursery school, and knew his letters. There is some discrepancy between these positive reports and PD's measured acuity, which when measured by the family doctor, that year and the next, was 20/200 in both eyes. His acuity, as measured by a second doctor at the age of nine was still 20/200, but a third doctor estimated his acuity at the age of 11 to be 20/100. The medical records leave it uncertain as to whether this discrepancy is due to whether or not PD's pupils were dilated during testing. Given that we measured his visual acuity as an adult to be approximately 20/80, it seems most likely that his vision as a child when dilated was closer to 20/80 or 20/100 than 20/200.

Fig. 1a shows a photograph of PD's cataracts (dilated more strongly than usual) that reveals the annular clear regions of pupil through which PD received his visual input. Pre-operatively PD tended to squint continuously, thereby replacing his 5 mm annular pupil by two much smaller (temporal and nasal) vertical slit-like pupils of much smaller diameter, as shown in Fig. 1b. When PD squinted, the position of the cataracts in each eye resulted in the temporal clear regions of pupil being larger than the nasal clear regions, in both eyes. The optical quality of the resulting retinal image was poor as a result of several (probably interacting) factors. First, PD received his visual input through the margins of his pupils where optical quality is much poorer, due to degradation of the image by spherical aberrations and wavefront distortions (Campbell & Green, 1965; Charman, 1991). Second, atropine dilation paralyzed accommodation and although he was astigmatic PD did not find corrective lenses useful pre-operatively. Consequently images were defocused on his retina. Third, because PD was hyperopic, the images from the two (nasal and temporal) clear spots in the pupil were not spatially superimposed on the retina, resulting in retinal double images (Fig. 12a). Even squinting, the overall quality of the retinal image remained poor, resulting in a resolution limit of 15 cpd.

As an adult PD was not legally blind before surgery, his pre-operative letter acuity was about 20/80 in each eye and he would have been classified as having low vision (bilateral amblyopia) according to most current definitions. He received enough visual stimulation, either before the cataracts opacified, or during his atropine regimen to provide pattern perception at low resolution, and therefore did not suffer from complete pattern deprivation amblyopia or the nystagmus associated with it (Levi, 1991). PD had no difficulty recognizing objects or three-dimensional forms even before the operation, though most fine spatial detail was lost.

PD used vision extensively before his operation. Even before surgery he biked regularly, and was an accomplished squash player. PD noted that squash suited him well because the dark ball was conspicuous against the white walls. Outdoor tennis was more challenging because of glare, and he avoided it. Clearly, the poor quality of his retinal images did not prevent him from engaging in rapid visually guided behavior. He had little

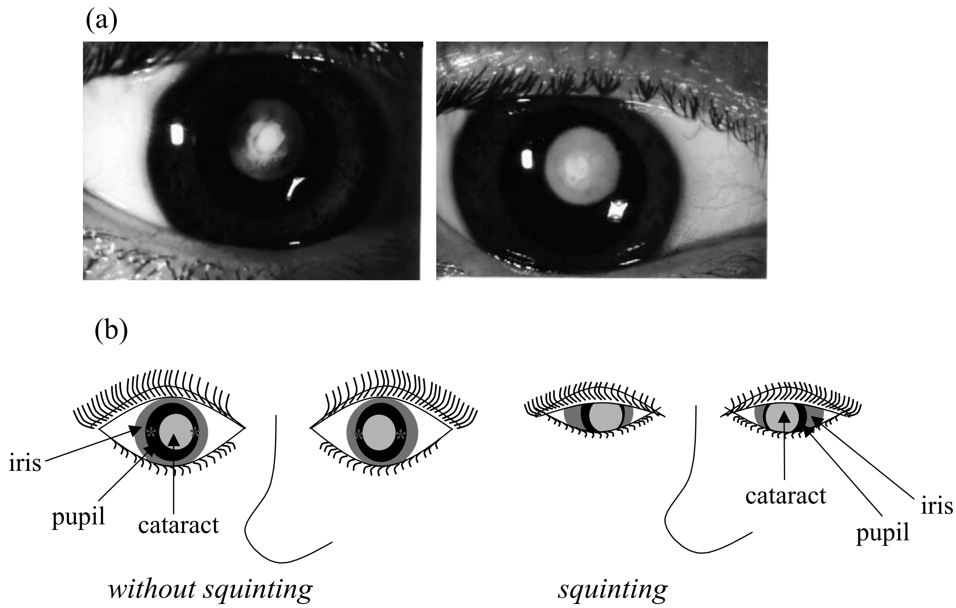

Fig. 1. (a) Photographs of PD's cataracts (taken by P.J. Saine, CRA of the Dartmouth Hitchcock Medical Center). PD's pupils were dilated, more strongly than by his normal bi-weekly atropine sulfate dilation, using a drop of atropine sulfate, 1% tropicamide and 2.5% phenylephrine. (b) The gray stars indicate how He–Ne laser light sources were introduced through clear regions on either side of the cataracts, as described in Experiment 4. Clear regions were larger temporally than nasally.

difficulty reading, though he tended to hold reading material at a very close viewing distance of approximately 20 cm. Because of his paralyzed accommodation, when reading at a close distance PD's myopia along the vertical meridian minimized vertical defocus. His horizontal hyperopia meant that at a close reading distance the images from the two slit-like pupils (squinting) in each eye were separated horizontally on his retina. Meanwhile, as discussed below, the Stiles–Crawford effect reduced the brightness of secondary images, and neural processes suppressed them still further, leaving a single, relatively clear image.

PD delayed cataract removal until 1998 because the lack of consensus between clinicians made him feel that the possible benefits did not merit the risk of surgery. PD's left cataract (the eye with poorer acuity) was removed on December 14, 1998 and his right eye's cataract was removed on January 27, 1999. There were only minor complications from surgery, posterior capsular opacification was removed by photodisruption (using a NdYAG laser) on the left eye on April 28, 1999, and on the right eye on May 26, 1999. Post-operatively his visual acuity was measured to be just worse than 20/40 with corrective glasses, and the improvement in his resolution limit was roughly similar. His correction after surgery was OD + 1.50S − 3.00C at 160°, OS + 3.25S − 3.75C at 5° in minus cylinder co-ordinates (corresponding to OD − 1.50S + 3.00C at 70°, OS − 0.50S + 3.75C at 95° in plus cylinder co-ordinates). A few optical factors may have affected his post-operative visual acuity, and PD suffered some post-operative opacification that prevented us carrying out certain post-operative measurements. Even with his best possible optical correction some of PD's astigmatism may have remained uncorrected.

2. Experiment 1—external and neural contrast sensitivity

PD's external and neural contrast sensitivity was measured before and after cataract removal to characterize how optical and neural factors limited PD's resolution (Campbell & Green, 1965). Neural contrast sensitivity was measured using laser interferometry, which bypasses the optics and can therefore be used to assess neural resolution in both normal observers (He & MacLeod, 1996; MacLeod, Williams, & Makous, 1992; Smallman, MacLeod, He, & Kentridge, 1996), and cataract patients (Cohen, 1976; Faulker, 1983; Green & Cohen, 1971; Halliday & Ross, 1983; Sherman et al., 1988).

In normal observers foveal optical and neural resolution are fairly closely matched (Campbell & Green, 1965; Le Grand, 1935): although increases in visual resolution can be obtained by bypassing the visual optics, such improvements are not large. Some of this match between optical and neural resolution seems to be the result of visual experience. If the range of spatial frequencies to which observers are neurally sensitive is hard-wired at birth or has a critical period ending before two years of age, then we would expect PD's *neural* resolution to be comparable to that of normal observers.

If, however, neural resolution remains contingent upon visual experience after two years of age then we would expect PD's neural sensitivity to show a fall-off at high spatial frequencies comparable to his pre-operative external contrast sensitivity function (CSF).

This matching of neural resolution to visual experience is thought to be the explanation of the "oblique effect", where normal observers are more sensitive to vertical and horizontal orientations than to oblique orientations. Similarly, early astigmatism has been shown to lead to permanent neural deficits and abnormal oblique effects (Freeman & Thibos, 1973; Freeman, Mitchell, & Millodot, 1972). PD's astigmatism was roughly along the vertical axis in both eyes (along the 70° axis in his right eye and the 95° axis in his left eye), and the double images on his retina were displaced horizontally. We therefore measured PD's neural resolution limit for a range of orientations to determine whether the different optical quality between his horizontal and vertical meridians resulted in a difference in neural sensitivity between the two meridians.

We retested PD for three months post-operatively to see whether his neural sensitivity to high spatial frequencies improved as he experienced them. Significant improvement would suggest that the matching of neural and optical resolution is a continuous process not limited to an early "critical period".

2.1. Methods

Vertically oriented sinusoidal gratings varying between 1 and 16 cpd were used to measure PD's external contrast sensitivity. These gratings were presented within a circular aperture of 3° of visual angle at a viewing distance of 13 ft in a dark room. The mean luminance of the display was 19.7 cd/m^2. Stimuli were temporally modulated by a 1 Hz square wave.

To measure PD's neural sensitivity as a function of orientation we measured his resolution limit for vertical interferometric fringes varying between 1 and 24 cpd. We also measured PD's neural resolution limit for eight different orientations (0°, 30°, 45°, 60°, 90°, 120°, 135°, 150°). Sinusoidal fringes were presented using a six-channel laser interferometer within a circular aperture of 3° with a mean retinal illuminance of 640 Td. As when measuring the external CSF, stimuli were temporally modulated at 1 Hz. Measurements were taken both pre-operatively, and then at regular intervals, up to three months post-operatively. We introduced the laser light source through clear regions of pupil. Only a small ($\leqslant 1$ mm) clear region was required, and because the light sources presented in the pupil plane were point sources the resulting sinusoidal grating pattern (fringes) remained relatively undisturbed by optical irregularities. Since the contrast of the interferometric pattern was determined by the ratios of the beam intensities, it was relatively unaffected by intensity reduction, and was reduced by scattering by a factor roughly independent of spatial frequency, see He and MacLeod (1996) for further details.

When measuring both the external and the neural contrast sensitivity function each fringe or grating was presented in a fixed order, and was presented approximately four times during each session. A method of adjustment was used: observers adjusted the contrast of each stimulus using a trackball mouse, until the orientation of the fringe or grating was just visible. Observers were given as much time as they liked to make each adjustment. All observers (in this, and in every other experiment described in this paper) had considerable practice with method of adjustment techniques. A forced choice orientation discrimination method (He & MacLeod, 1996) was also used to obtain PD's neural sensitivity function, and results were virtually identical.

Pre-operatively PD dilated his pupils with atropine, in his customary fashion. Post-operatively, where appropriate, PD used his best possible optical correction. Control subjects had normal, or corrected-to-normal acuity. These same dilation and corrective procedures were used in all the experiments described in this paper.

2.2. Results and conclusions

Fig. 2a and b shows PD's external CSF for his left and right eyes respectively, before and after surgery. Before surgery PD's CSF showed a sharp fall-off for spatial frequencies above 5 cpd. Fig. 2c shows the sensitivity ratio comparing sensitivity before and after surgery, for both the left and the right eye. In both eyes, improvement increased with spatial frequency. The left eye was initially much worse than the right, and improved much more. After surgery, high spatial frequencies were far less strongly attenuated, though there was still an observable difference between PD's contrast sensitivity function and that of normal observers.

Fig. 3a and b shows PD's neural CSF for his left and right eyes respectively, before and after surgery. A normal observer (HSS, right eye) is represented by unfilled symbols in Fig. 3b. PD's neural sensitivity barely changed post-operatively. PD's neural sensitivity is comparable to that of HSS for fringes with spatial frequencies lower than 8 cpd. PD's greater than normal sensitivity to very low spatial frequencies may be due to neurons that would normally be sensitive to higher spatial frequencies shifting their sensitivity towards lower spatial frequencies. Such a shift might occur as a result of competition between spatial frequency channels during development (Greenlee, Magnussen, & Nordby, 1988; Wilson, 1988).

PD's neural sensitivity begins to decline at 5 cpd, and by 10 cpd HSS's neural sensitivity is far higher than

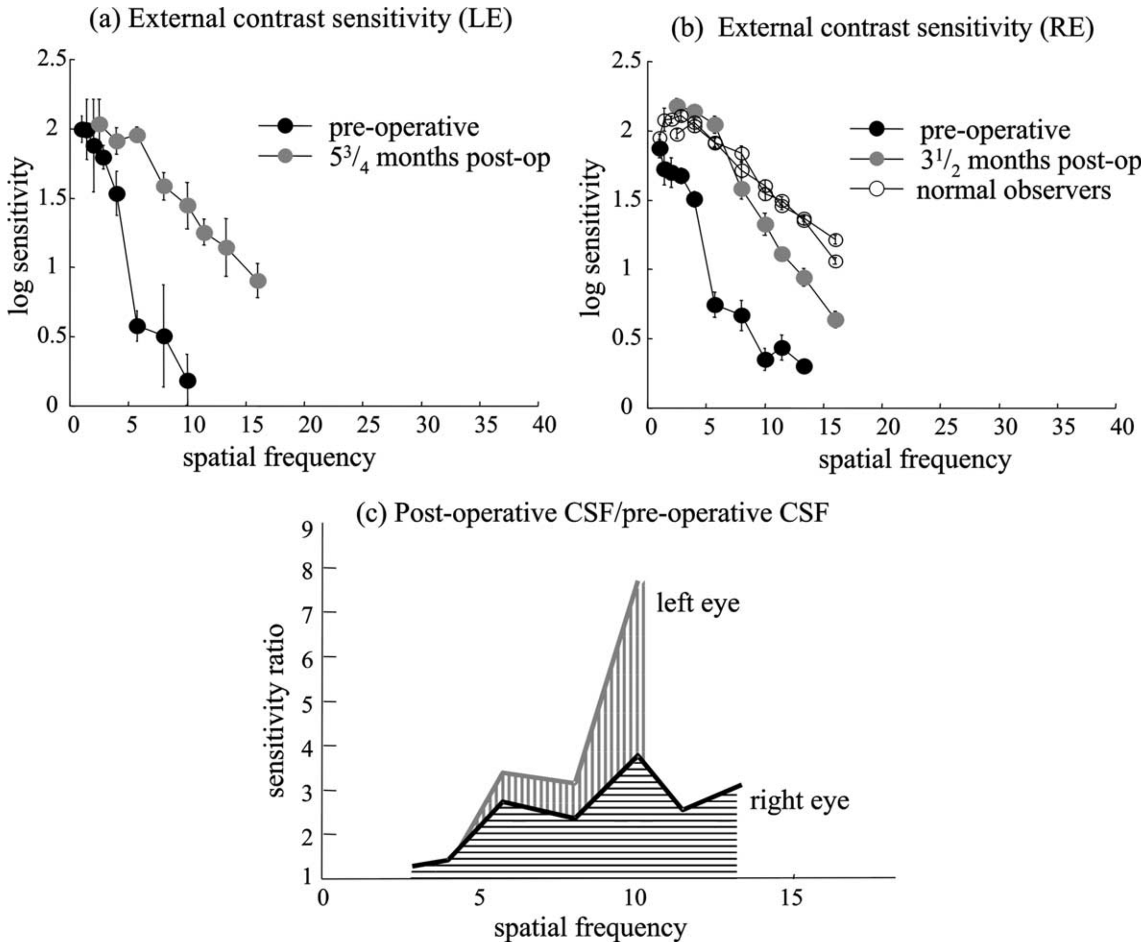

Fig. 2. The external CSF of PD measured pre- and post-operatively, as compared to two normal observers. The horizontal axis represents spatial frequency; and the vertical axis represents log sensitivity. Black filled symbols represent PD's pre-operative performance, gray symbols his post-operative performance, and unfilled symbols the performance of normal observers (IF and HSS). (a) Left eye. (b) Right eye. Standard error bars are shown. (c) The sensitivity ratio (post-operative CSF/pre-operative CSF) for both the left and right eye. Note the change of scale along the horizontal axis.

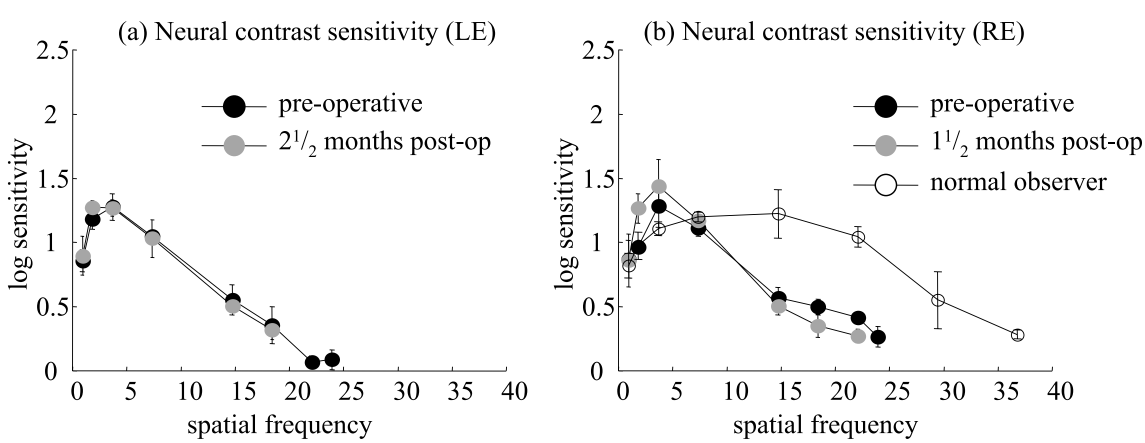

Fig. 3. The neural CSF of PD measured pre- (black circles) and post-operatively (gray circles). The horizontal axis represents spatial frequency and the vertical axis represents log sensitivity. (a) Left eye. (b) Right eye. The neural CSF of HSS (right eye) is shown for comparison (empty circles). Error bars are shown.

PD's, both pre- and post-operatively. Similarly, Ellemberg, Lewis, Maurer, Lui, and Brent (1999) found greater sensitivity deficits for high spatial frequencies in children who had been diagnosed (and treated) for bilateral cataracts in infancy. PD's low neural sensitivity for high spatial frequencies suggests that the matching of neural sensitivity to optical limitations is at least partially the result of visual experience after the age of two. Given that the normal resolution limit for two-year olds is approximately 22–25 cpd: close to PD's neural resolution limit (Mayer & Dobson, 1982); it seems possible that PD's optics were able to supply the full spatial bandwidth to which the developing neural system is sensitive until he reached that age.

Overall absolute sensitivity was lower in our interferometer both for PD and for the normal observers (including HSS). This was most likely due to speckle masking (Williams, 1985). When shifted along the vertical axis, the shape of PD's neural sensitivity closely matched the shape of his post-operative CSF, suggesting that almost all his post-operative resolution loss was due to neural rather than optical factors.

As shown in Fig. 4, PD's self-adjusted resolution limit for interferometrically presented vertical fringes was about 15.5 cpd (LE) and 17 cpd (RE). In contrast his resolution limit for horizontal fringes was 26 cpd (LE) and 23.5 cpd (RE). Pre-operative measurements were similar, and these neural effects lasted for a considerable period post-operatively: PD's resolution limit as a function of orientation was measured 20 (RE) and $21\frac{1}{2}$ (LE) months post-operatively, and we found no reduction in this oblique effect over time. Again, this matching of neural sensitivity to PD's optical limitations suggests that visual experience after the age of two has a significant effect on neural contrast sensitivity.

We measured PD's neural sensitivity regularly for three months post-operatively. Although we found a very small improvement in PD's neural contrast sensitivity shortly after cataract removal, there was no slow long-term improvement in neural sensitivity. The improvement found shortly after surgery might have resulted from post-operative exposure to high spatial frequencies. However this improvement was relatively small, and we cannot entirely exclude the possibility that pre- and post-operative differences were due to a failure to present the laser point sources through entirely cataract free regions pre-operatively.

PD's relative insensitivity to high spatial frequencies, and his abnormal oblique effect suggest that his neural resolution was, to a certain extent, matched to his retinal input. However PD remained neurally sensitive to spatial frequencies (above 15 cpd), well above his pre-operative external resolution limit. One possibility is that PD's cataract only began forming around two years of age, when PD's neural resolution limit would have been around 22–25 cpd, and that there was no improvement or deterioration in his neural resolution after that age. Alternatively, if PD had spatial-frequency-selective channels tuned for 15 cpd (the highest spatial frequency that passed through his optics), they might be expected to show some residual sensitivity up to 25 cpd. A third possibility is that cortical pattern analyzers can be developed and maintained even for spatial frequencies high enough to undergo severe optical attenuation, as the results of He and MacLeod (2001) and Smallman et al. (1996) suggest for normal vision.

Given that there was no evidence of PD's cataracts at 13 months, our data suggests that the "critical period" for contrast sensitivity extends beyond early infancy, consistent with the observation that infant resolution limits are still increasing at two years of age (Mayer & Dobson, 1982). However, plasticity as an adult seemed to be very limited: neither PD's neural sensitivity to high spatial frequencies, nor his relative insensitivity to vertical gratings had improved noticeably three months after his cataracts were removed.

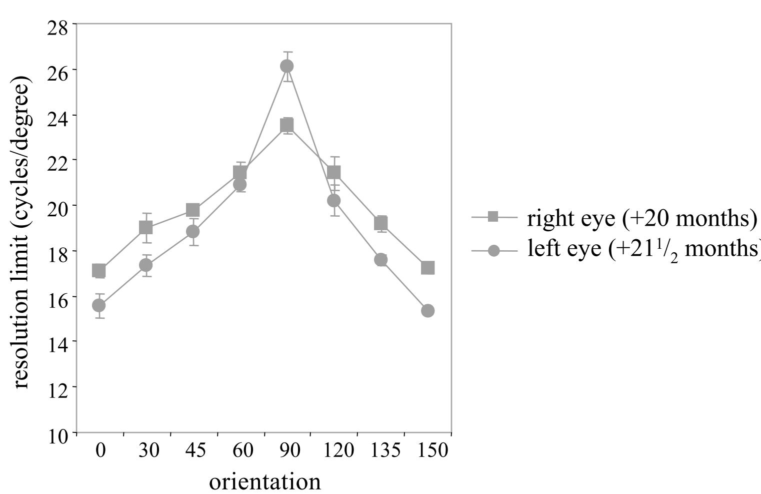

Fig. 4. Neural sensitivity as a function of orientation. The horizontal axis represents orientation in degrees from vertical and the vertical axis represents PD's resolution limit—the highest spatial frequency just visible by PD. Circular symbols represent PD's resolution limit measured using the left eye, square symbols represent PD's resolution limit measured using the right eye.

3. Experiment 2—the appearance of edges: the subjective square wave

Pre-operatively, PD's optics severely attenuated all high spatial frequencies (Fig. 2), resulting in sharp edges being blurred on his retina. However, PD did not perceive such edges as being blurred pre-operatively. Fig. 5 shows drawings of the brightness distributions that PD saw on the screen though his left (newly operated) eye and his right eye (still pre-operative). When looking through his right, *pre-operative* eye, a sharp edge appeared sharp. Through his post-operative left eye PD spontaneously noted pronounced perturbations in brightness near edges, "*looking at a bright square against a black background it seemed like the sheet was brighter near the edge, the division between the white and the black. I suppose this was due to the fact that I had never seen that sharp a demarcation before*". These perturbations near sharp edges were only visible through the operated eye. PD also remarked that post-operatively the white centers of closed letters such as p, o and q appeared noticeably brighter than the white paper in the uniform surround for several months post-operatively.

The sharp appearance of edges pre-operatively suggests that PD compensated neurally for the high spatial frequency attenuation of his pre-operative optics. Both normal observers and some astigmatics show contrast constancy, indicating neural compensation for optical attenuation (Georgeson & Sullivan, 1975). Some amblyopes also compensate for their reduced sensitivity to high spatial frequencies, demonstrating contrast constancy for suprathreshold stimuli (Hess & Bradley, 1980; Leat & Millidot, 1990). The post-operative "scalloping" observed by PD suggests that he continued to compensate neurally for his pre-operative optics even after his cataracts were removed. Neurally overcompensating for his post-operative optics by boosting the apparent contrast of higher spatial frequencies would result in scalloping of sharp edges. Although PD's scallops resembled Mach bands, they probably have a different neural origin since Mach bands are much weaker for sharp edges than for luminance gradients (Fiorentini & Zoli, 1966; Mach, 1897; Ratliff, 1984; Ratliff, Milkman, & Rennert, 1983).

It is still an open question whether observers continuously compensate for slow changes in their individual CSF over time. Galvin, O'Shea, Squire, and Hailstone (1999) found that observers' contrast constancy does not change within a matter of minutes: observers' decisions about blurriness were not affected by the context of a scene only containing low-pass filtered edges. Given that a square wave appeared scalloped to PD, we thought it likely that a suitably low-pass filtered wave might appear square. We tracked the extent of PD's post-operative scalloping quantitatively over time by asking him, and three normal observers to create a wave that appeared phenomenally "square", consisting of subjectively uniform dark and bright regions, with a sharp edge between them.

3.1. Methods

The stimulus consisted of four cycles of a wave pattern, created by adding one-dimensional white noise to a square wave pattern with a spatial frequency of 0.23 cpd (see Fig. 6). The midpoint of each dark and bright region had a fixed luminance of 26 and 105 cd/m^2 respectively. Using the buttons on the bottom of the screen observers adjusted the brightness of narrow strips (1/20th of the width of one cycle). The luminance values of the waveform were linearly interpolated between the midpoint of each strip. Observers were asked to "clean up the noise" and make the pattern on the screen look like a square wave, i.e. make dark and light regions each appear uniformly bright, with a sharp edge between them. When observers were satisfied that the wave looked square, the luminance profile was saved. Observers were given as much time as they liked for each adjustment. The experiment was carried out monocularly at a distance of 75 cm in a darkened room.

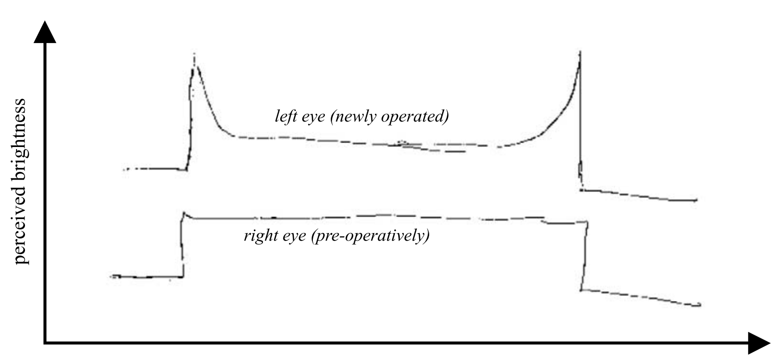

Fig. 5. PD's drawing of the appearance of the brightness profile of a one-dimensional slice filling a uniformly white computer monitor in a dark room. The upper drawing was done using his left, newly operated eye, the lower drawing was done using his right, pre-operative eye.

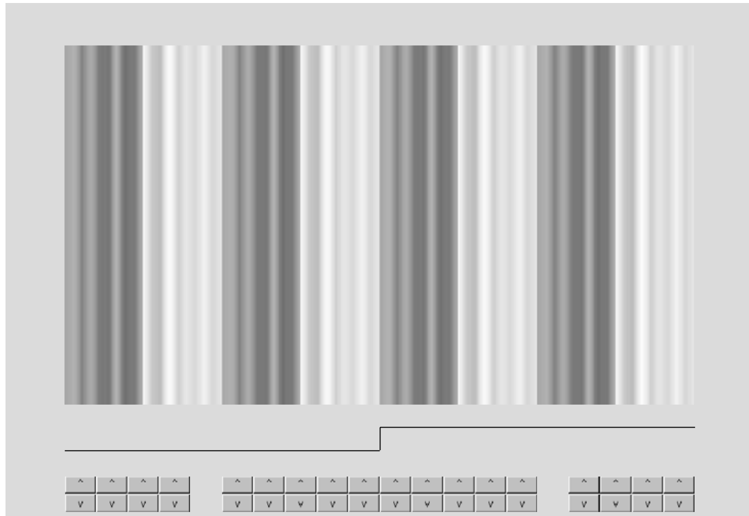

Fig. 6. Stimulus used to test oversharpening of edges in PD. Observers used buttons on the bottom of the display to adjust the luminance of thin vertical strips. Observers were asked to adjust the luminance profile so as to make a subjectively square wave—i.e. to make the dark and bright regions appear uniform.

3.2. Results and conclusions

Fig. 7 shows square wave settings made by PD (a) and a normal control observer IF (b) monocularly using the right eye. Performance was very similar using the left eye. The performances of two other normal observers (HSS and JMB) were similar to IF. As predicted, the edges of an apparent square wave are more blurred for PD than for IF.

The filled circles of Fig. 8a (left eye) and b (right eye) represents the settings presented in the Fourier domain. If observers set a perfect square wave the points would lie along the line $y = 1$. A ratio of less than one means that the observer required, at that spatial frequency, less amplitude in the external stimulus than is present in a physical square wave. A setting of greater than one means that the observer required too much physical contrast at that spatial frequency. PD had to reduce the amplitudes of high spatial frequency components to create a perfect subjective square wave, consistent with the blurred edges of the square wave in Fig. 8a. In comparison, Fig. 8c shows the amplitude of each spatial frequency component as set by IF: the points fall close to the line $y = 1$.

Fig. 10a shows performance on the square wave task $4\frac{3}{4}$ and 15 months post-operatively. There was still evidence of neural overboosting of high spatial frequencies 15 months post-operatively, but it was now much reduced in magnitude. Normal observers' CSFs do change naturally with age (Elliott, 1987; Elliott, Whitaker, & MacVeigh, 1990; Morrison & McGrath, 1985), motivating plasticity within contrast compensation. But since changes in an observers contrast sensitivity function are normally very gradual, it is not entirely surprising that

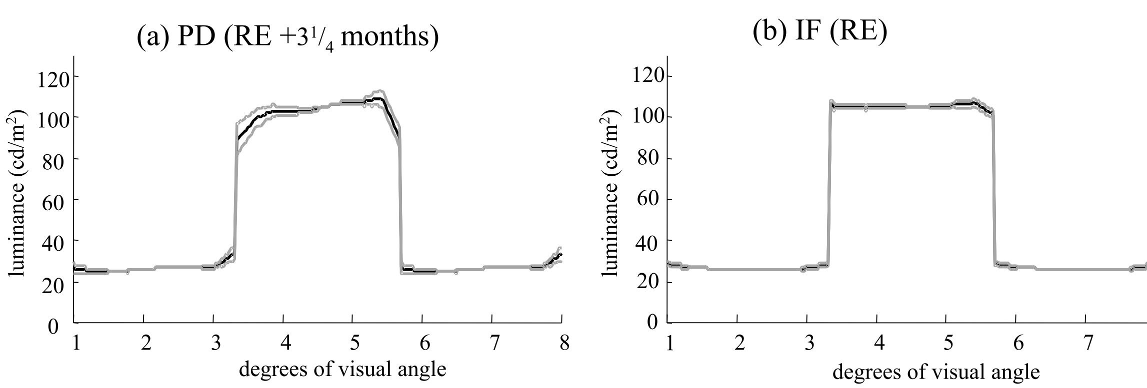

Fig. 7. (a) Luminance profile for one and a half cycles of a subjective square wave as set by PD using his right eye. (b) Luminance profile for a subjective square wave as set by normal observer IF (right eye). Gray lines indicate the standard error.

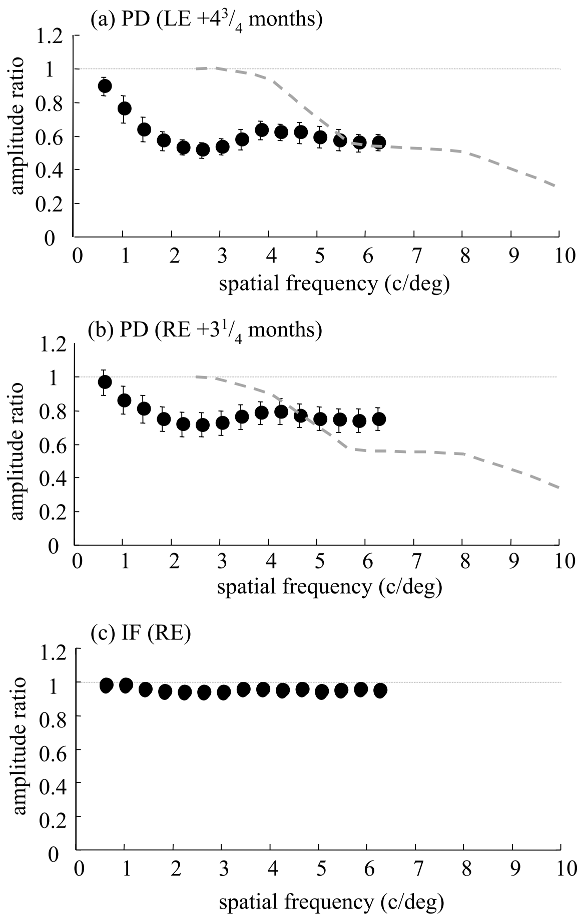

Fig. 8. Subjective square waves as made by observers presented in the Fourier domain. The horizontal axis represents spatial frequency, the vertical axis represents the amplitude ratio—the amplitude of each Fourier component divided by the amplitude of that component in a true square wave. Only the components present in a true square wave are shown. Filled circles show (a) settings made by PD using his left eye. (b) Settings made by PD using his right eye. (c) Settings made by IF using her right eye. Error bars are shown. The dashed gray curve shows the theoretical prediction for PD continuing to neurally compensate for his pre-operative optics in these post-operative tests.

PD's neural plasticity lagged behind the abrupt change in his optics. The suggested time constant for this plasticity is on the order of one year.

If the scalloping PD saw post-operatively was due to his continuing to compensate for his pre-operative optics post-operatively, then his overemphasis of high spatial frequencies should be consistent with the change in his CSF that was introduced when the cataracts were removed. We calculated the overemphasis of high spatial frequencies we would expect from PD if he perfectly compensated for his pre-operative optics and did not compensate at all for the post-operative change in his optics. We used PD's pre- and post-operative external CSFs as estimates of his pre- and post-operative optical attenuation. The dashed gray curve represents predictions based on the assumption that the compensation is the same for the two eyes, and is the average of what is appropriate for the two eye's pre-operative optics, as might be expected if the compensation is applied at a site where the signals from the two eyes converge. There was only a weak correspondence between the predictions made by the change in PD's contrast sensitivity, and his settings of an apparent square wave. We also calculated predictions based on independent compensation in each eye, but such predictions bore even less resemblance to the data and are not shown.

One limitation of the square wave task described above is that the energy required at each spatial frequency falls off inversely with frequency. At higher spatial frequencies very little energy is needed to make a square wave; measuring deviations from a perfect square wave for the high spatial frequency components therefore involves measuring very small quantities. We therefore measured PD's performance on a contrast matching task using sine wave gratings of high contrast.

4. Experiment 3—contrast matching

Contrast constancy (Georgeson & Sullivan, 1975) is the invariance of perceived contrast with spatial frequency for sine wave gratings sufficiently above the (frequency-dependent) detection threshold. Contrast constancy implies that normal suprathreshold vision compensates well for optical attenuation of high spatial frequencies. In PD, any failure to compensate fully for the change in his optics should lead to a failure of contrast constancy.

4.1. Methods

Observers matched the contrast of two grating patterns presented simultaneously in the top and bottom half of a display. The test grating could appear in either the top or the bottom half of the display. The relative position of the reference and the test grating varied randomly, with a small asterisk to the side of the stimulus indicating which stimulus was the test grating. The reference grating was always at a contrast of 20%. Observers adjusted the contrast of the test grating to match the contrast of the reference grating. Gratings of 0.41 and 2.1 cpd were used as reference gratings. The test gratings ranged in frequency between 0.2 and 15 cpd. Both test and reference gratings were presented within rectangular apertures subtending 7.8° horizontally and 2.2° vertically. Observers were seated at a viewing distance of 1.58 m in a dimly lighted room. The mean luminance of the monitor was 66 cd/m^2. Stimuli had an abrupt temporal onset and offset, and were present as long as was necessary for observers to adjust the comparison stimulus to match the standard stimulus. Each grating was presented in a random order several times in each session.

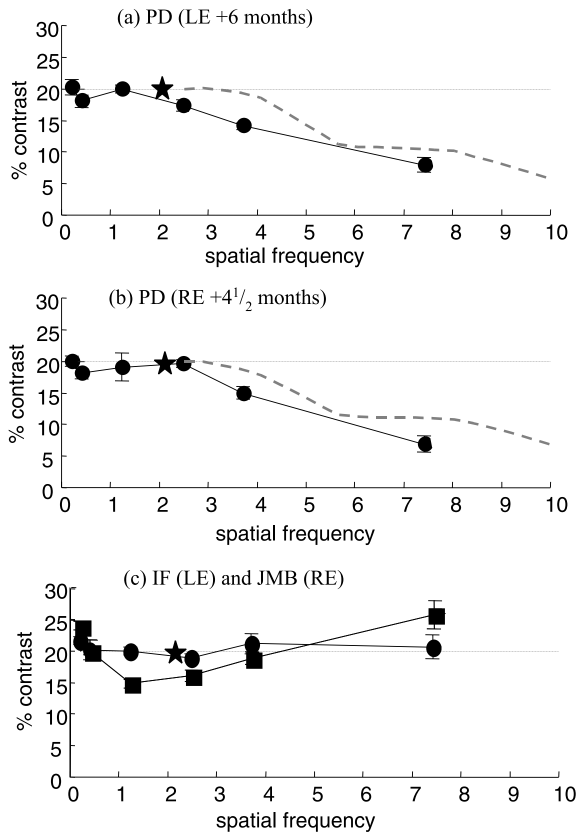

Fig. 9. Observers adjusted the contrast of a grating of variable spatial frequency to match that of a grating of 2.1 cpd at 20% contrast. (a) The matching contrasts of PD using his left eye. (b) PD using his right eye. (c) Two normal observers. A third observer, HSS (not shown) also demonstrated contrast constancy. Error bars are shown. The dashed gray curve shows the theoretical prediction for PD continuing to neurally compensating for his pre-operative optics in these post-operative tests.

4.2. Results and conclusions

The solid symbols in Fig. 9 show contrast matches set by PD and two normal observers for a reference grating at 2.1 cpd (indicated by a star). Perfect contrast constancy is indicated with a black line. Contrast matches using a 0.41 cpd reference grating were very similar and are not shown. Consistent with previous studies (Brady & Field, 1995; Georgeson & Sullivan, 1975), matches made by our three observers were independent of spatial frequency, and lie near the line of perfect constancy (with the exception of the lowest spatial frequency for HSS, data not shown). Unlike the other two observers PD did not show contrast constancy. Rather, he underestimated the contrast needed to match high spatial frequency gratings with a grating of 2.1 cpd. At spatial frequencies above 15 cpd PD had difficulty seeing the comparison grating. At these spatial frequencies his contrast matches were unreliable and are not shown. Deviations from constancy are smaller than suggested by PD's apparent square wave settings, but are again in the direction that we would expect if PD failed to compensate fully for the change in his external CSF caused by the removal of his cataracts. The dashed gray curve in Fig. 9a and b represents the deviation from constancy we would expect from PD if he were failing to compensate for the change in his optics.

Fig. 10b shows performance on the contrast matching task $4\frac{1}{2}$ and $13\frac{1}{2}$ months post-operatively. As with the square wave task, although there was a gradual reduction of the effect, PD continued to neurally "overboost" high spatial frequencies for a considerable period of time.

5. Experiment 4—Stiles–Crawford measurements

While we were finding two clear regions in the pupil of the right eye (to measure his pre-operative neural CSF) PD spontaneously reported that the laser light appeared distinctly "*brighter and whiter*" when presented through the larger temporal clear regions compared to when it was presented through the smaller nasal regions. He reported the same phenomenon in the left eye. Differences in the apparent brightness and hue of lights entering the pupil from different points are termed the Stiles–Crawford effects of the first and second kind (SC I and SC II), respectively, and are known to reflect cone photoreceptor alignment (Enoch & Lakshiminarayanan, 1991; Enoch & Stiles, 1961; Stiles, 1937; Stiles & Crawford, 1933). The waveguide properties of the photoreceptors endow them with a directional selectivity for incident light (Toraldo de Francia, 1949; Snyder & Pask, 1973). In adults with normal visual experience the cones are pointed towards the center of the pupil (Laties, Liebman, & Campbell, 1968), and consequently lights of constant physical intensity appear brightest when presented in the center of the pupil. Lights also appear both shifted in hue and in saturation from a combination of self-screening and Bezold–Brücke effects (Enoch & Stiles, 1961; Stiles, 1937). This photoreceptor alignment makes functional sense because the center of the pupil normally marks the centroid of the distribution of incident light directions at any retinal point; having the receptors aligned there maximizes their absorption of light while minimizing the effects of light scatter within the eye. PD's temporally displaced Stiles–Crawford effects suggested that his photoreceptors, too, were aligned towards the incident light, in his case, from a region close to the temporal pupil margins (see Fig. 11a).

Others have found displaced SC I effects associated with displaced pupils (Bonds & MacLeod, 1978; Dunnewold, 1964), and others have also documented incomplete receptor realignments towards artificial pupils (Applegate, 1983; Applegate & Bonds, 1981; Enoch & Birch, 1981). PD's case was unique, not only in that his displaced pupils were naturally occurring and lasted

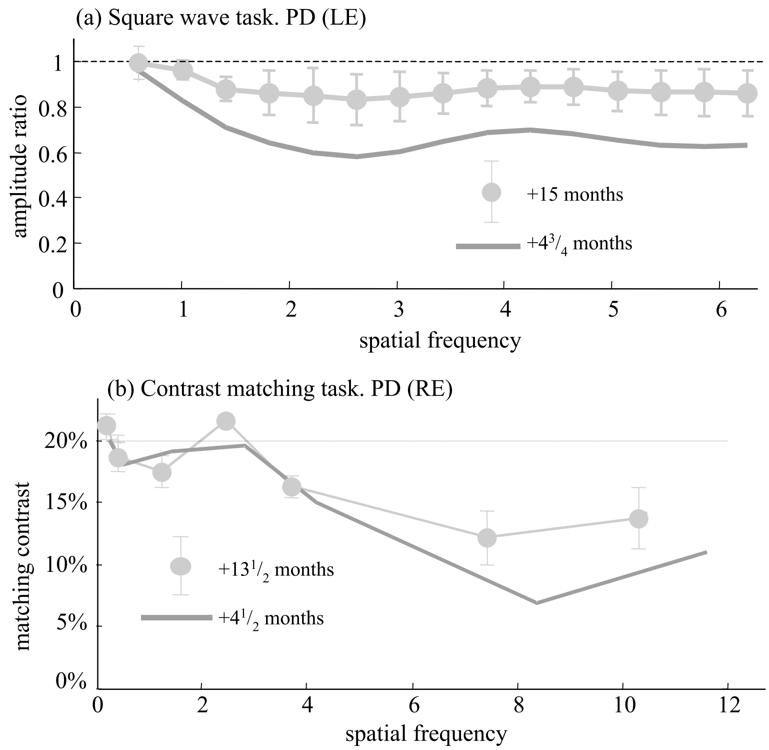

Fig. 10. (a) PD's performance on the square wave task using the left eye $4\frac{3}{4}$ months post-operatively (from Fig. 8—dark gray line), and after 15 months (light gray symbols). (b) Performance on the contrast matching task using the right eye $4\frac{1}{2}$ months post-operatively (from Fig. 9—dark gray line) and $13\frac{1}{2}$ months post-operatively (light gray symbols). Error bars are shown.

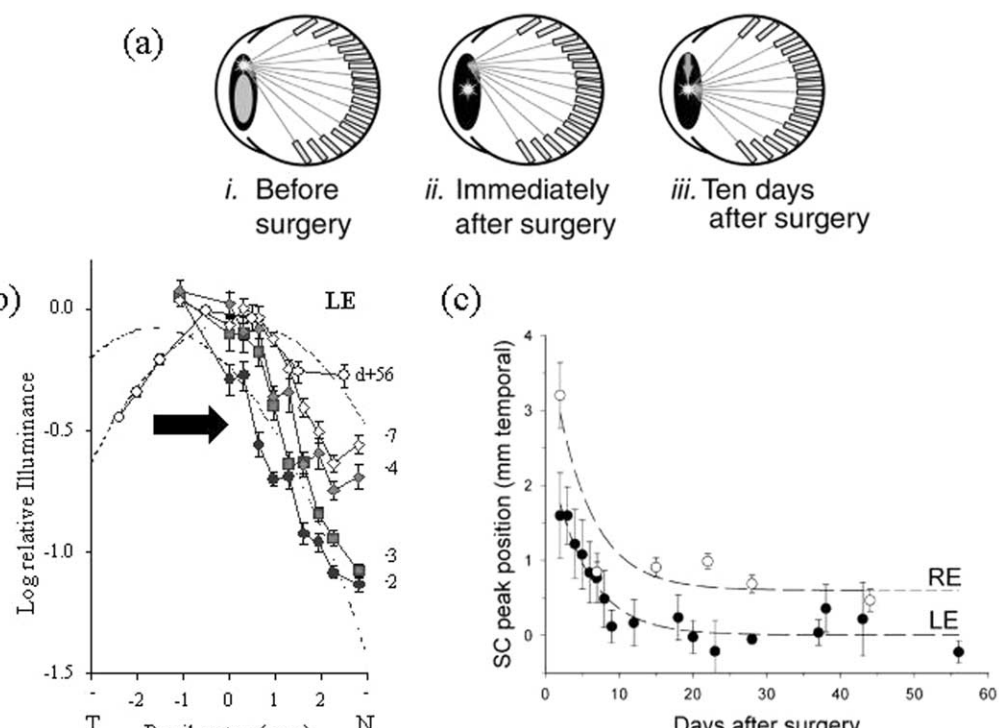

Fig. 11. (a) Schematic horizontal cross-sections through PD's eyes. (i) Before surgery, the receptors were aligned (dashed gray lines) with the brightest pupil location ('sun') in the temporal margins. (ii) Immediately after surgery, the brightest location shifted to the pupil centers but the receptors retained their skewed alignment. (iii) Over 10 days, the receptors realigned with the bright pupil centers (the arrow depicts the shift measured from b and shown in c). (b) A subset of the SC I functions measured in the left eye. Data from second day after surgery (d + 2), third, fourth, seventh and 56th days are shown to illustrate the progressive nasal-ward shift of the SC functions. Dashed lines represent parabola fit to the functions (d + 2 on the left, and d + 56 on the right). Pre-dominant receptor alignment in the pupil plane were estimated from the peaks of the parabolas. (c) Peaks of the SC I functions over time for both eyes. (a) and (c) are reprinted by permission from Nature (Smallman, MacLeod, & Doyle, 2001) copyright (2001) Macmillan Magazines Ltd.

many years, but also in that they were binocular. We examined whether PD's receptors would dynamically realign towards his pupil centers after surgery. Portions of this work have previously been reported (Smallman et al., 2001).

5.1. Methods

SC I functions were measured using a conventional brightness matching task. PD matched the intensity of an 8 Hz flickering, He–Ne 632.8 nm test laser point source to that of a counter-phase flickering reference point source of fixed 640 Td intensity. The beams filled 3° circular fields of foveal retina. The test was traversed across 10 different positions spanning the horizontal central meridian of the pupil, with eight matches being made at each test position. Test and reference were viewed in the dark, with no surround. PD's head was carefully aligned daily and was stabilized using a dental impression.

Immediately after surgery on the left eye, PD avoided the use of mydriatics to avoid surgical complications, so we could only traverse the test beam over a restricted portion of PD's pupil (3 mm). Twenty-three days after left eye surgery, PD began applying mydriatics (1% tropicamide) before a testing session and the test beam was traversed 6 mm across his (now fully dilated) pupil. Data was gathered less frequently on the right eye but all of it was gathered with a fully dilated pupil using mydriatics.

5.2. Results

Before surgery, only one data point on a complete SC I function could be measured due to the presence of the cataracts: lights appeared brighter by 8-fold (left eye) and 10-fold (right eye) when presented temporally as opposed to nasally. The day after surgery, in both eyes, PD's SC I functions were still aligned towards the temporal margins of his pupils: there was still an 8-fold mismatch in the intensity required to make lights match in brightness across the pupil. This established that we had not inadvertently been measuring a mismatch caused by passing the light source through part of the edge of a cataract pre-surgically.

As shown in Fig. 11b, Parabola of the form $\log(\text{sens}) = ax^2 + bx + c$ were fit to each day's complete SC I function, where x is test position in the pupil and a represents receptor spread (Applegate & Lakshminarayanan, 1993; Stiles & Crawford, 1933). Dashed lines represent parabola fit to the functions for +2 days on the left, and for +56 days on the right. Peak receptor position in the pupil was inferred from the peak of the parabola. Because until day 23 we could only measure SC I functions over only 3 mm in the left eye we could not reliably fit both a and b as free variables based on the data. We therefore set a to the mean of the post-day 23 left eye data a estimates, and then fit the data to find b.

Given that PD possessed two clear regions of pupil in each eye pre-operatively it seemed plausible that while the majority of receptors aligned themselves towards the brighter temporal regions of pupil, a minority might have oriented towards the dimmer nasal regions. If this were the case then we would expect, (1) increased receptor disarray in PD compared to normals, and (2) that this directional disarray would decrease as both sets of receptors converged towards the pupil centers. However, measurements in the right eye found no evidence for a subset of nasally aligned photoreceptors. First, comparison of the directionally selective adaptation effects using nasally and temporally presented light sources were inconsistent with the presence of a subset of nasally aligned photoreceptors whose sensitivity would be selectively suppressed by nasally presented light (MacLeod, 1974). Second, the spread of the SC functions (a) did not change over the course of the right eye's realignment. These data suggest that PD's receptors all realigned towards the brightest pupil location.

Fig. 11c shows the peaks of the SC I functions in both eyes as a function of time after surgery. The left eye SC peak migrated over 1.6 mm nasally to the now bright pupil center. The right eye SC peak migrated further towards the pupil center (2.6 mm), but did not migrate to a fully central position, stabilizing instead at 0.6 mm temporal. Adults with normal visual experience exhibit a spread of SC peak positions, with a peak that is, on average, 0.5 mm nasal (Applegate & Lakshminarayanan, 1993). At birth, primate photoreceptors are aligned towards the pupil centers (Laties & Enoch, 1971). Presumably then, what we measured was the second major realignment of PD's photoreceptors. The first major realignment probably occurred sometime during the first three years of life, as the cataracts opacified and the receptors migrated temporal ward to align on the brighter clear temporal regions of pupil.

The shifts we measured in the pupil corresponded to an angular shift at the retina of 4° for the left eye's receptors and 6.5° for the right eye's receptors. What could mediate such shifts? As shown in Fig. 11c, we characterized the shift in the peak receptor position (p) as a function of time (t) with exponentials of the form $p = \text{peak}_{\text{end}} + (\text{peak}_{\text{start}} - \text{peak}_{\text{end}})e^{-t/k}$, which fit the data well ($r^2 > 0.88$). The time constant for the realignment process was five days for both eyes. These curves may provide insight into the mechanism underlying the shifts because the good fits by exponential functions imply that the rate of receptor realignment was proportional to the distance remaining to the bright pupil centers. Thus whatever the biophysical processes underlying these shifts, they are likely phototropic, and may be under the control of a simple biophysical feedback signal (Applegate & Bonds, 1981), similar to the processes by which plants track the sun. Receptor motility for a variety of non-human species is modulated by actin filaments (Burnside & Nagle, 1983; Laties & Burnside, 1979). For example, in plants, phototropism is mediated by differential growth (Dennison, 1979). Analogous actin filament-mediated differential longitudinal growth within the retina could also make photoreceptors phototropic.

6. Experiment 5—monocular suppression of secondary images

As mentioned above, before his cataracts were removed PD was astigmatic, being vertically myopic and horizontally hyperopic. Consequently, the primary nasal and temporal images from the two clear spots in the pupil were not spatially superimposed on the retina (especially in close work, as in reading, where his paralyzed accommodation could not help align them). Images through the temporal clear regions in his pupils were displaced nasally in the visual field, compared to images though his nasal clear regions, as shown in Fig. 12a. PD seemed remarkably unaware of these double images pre-operatively. He recalled that he first becoming aware of his diplopia when he happened to be looking closely at some stray chalk dots on a blackboard: "*I do not know why I was looking at these dots on the chalkboard but I remarked on how there are these bunches of double dots and after a brief discussion it turned out that I had always had this problem, I had just never been aware of it*".

Fig. 12b shows drawings of PD's subjective experience of looking at a bright vertical line through his two eyes pre-operatively, both when he was in his normal "squinting mode", and when he relaxed his face. Through the right eye the secondary image of the line appeared to the right of the bright primary image. Through the left eye the secondary images appeared to the left of the primary image, and diplopia was more salient. Pre-operatively PD's displaced Stile–Crawford functions may have played a role in weakening these secondary images. In any case PD reported being largely unaware of these secondary images. We therefore examined whether we could find evidence for active neural suppression of these double images.

6.1. Methods

We measured PD's post-operative ability to detect a faint test line that was either to the right or the left of a brighter, standard line. Two lines were presented

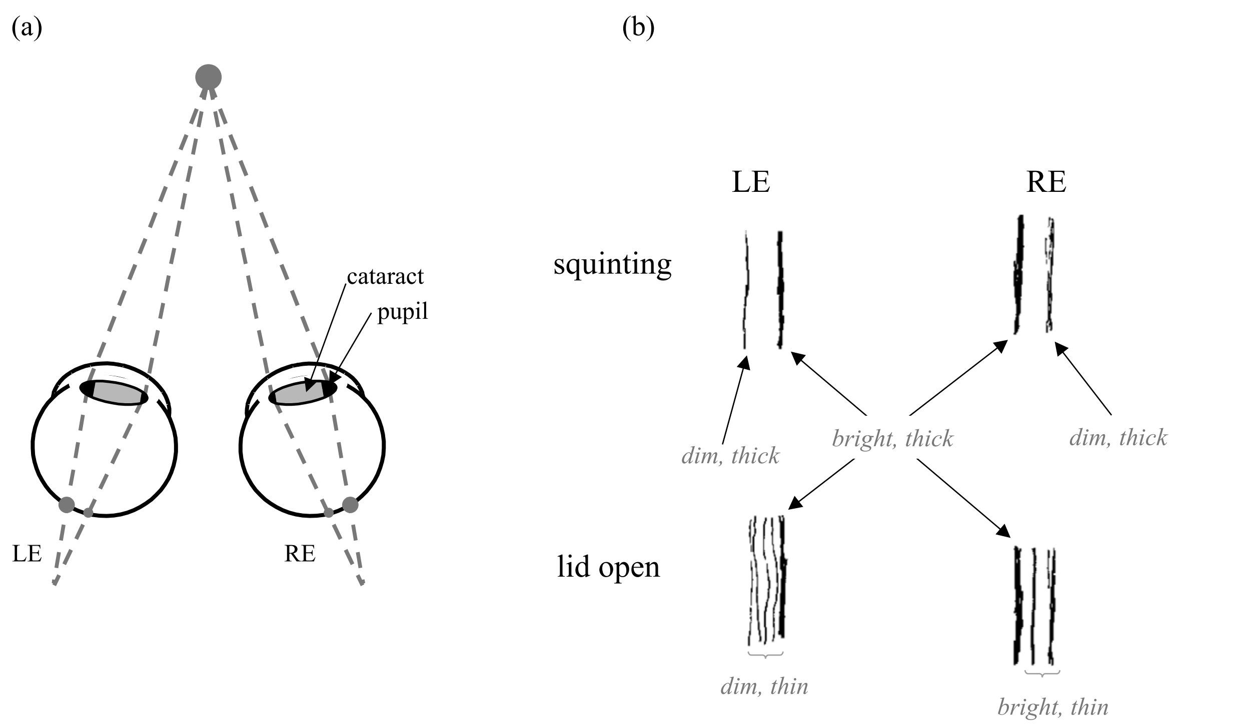

Fig. 12. (a) Cross-section showing how PD's horizontal hyperopia resulted in double images of vertical lines on PD's retina. (b) PD's drawings of what a vertical white line on a black background looked like, reversing black and white, when squinting (top panels), and when not squinting (bottom panels). Right panels, right eye; left panels, left eye. The temporal clear regions of pupil produced the brighter retinal images, so the secondary double images were displaced temporally on the retina. Consequently, in each eye secondary double images appeared to be displaced towards the nasal visual field.

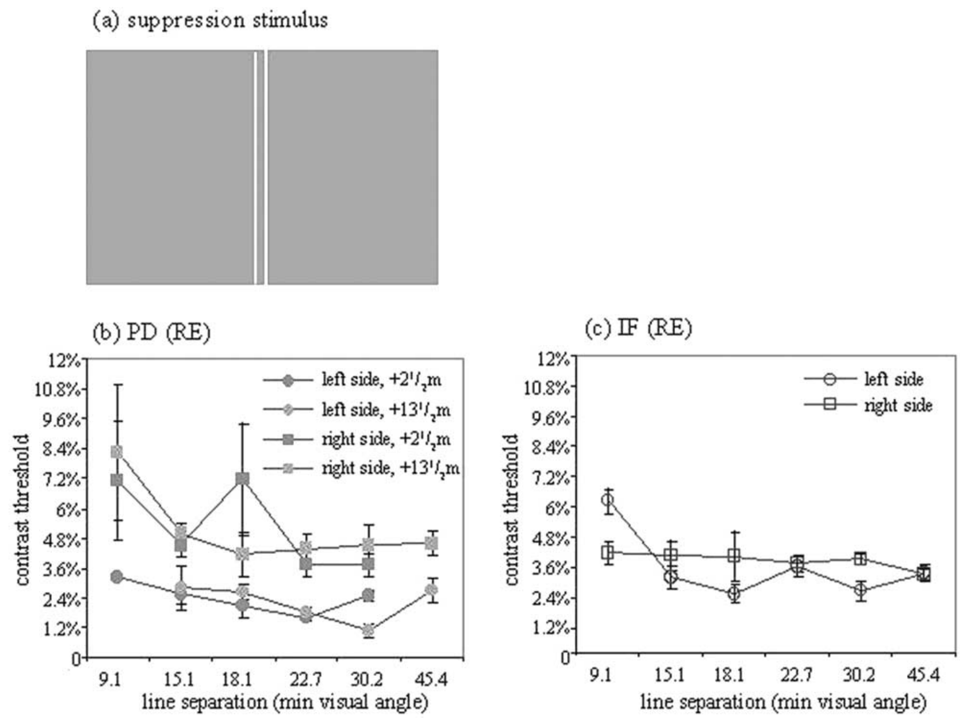

Fig. 13. (a) The suppression stimulus. (b) Ability to discriminate whether a faint line is to the right or the left of a bright line as a function of contrast for PD. The horizontal axis represents the distance separating the two lines in minutes of visual angle, and the vertical axis represents the 84% threshold at which observers could reliably tell whether the faint comparison line was to the left or the right of the bright standard line. The standard deviation of the best fitting cumulative normal function is shown. Performance when the test line was to the right of the standard is shown with square symbols, performance when the test line was to the left of the standard is shown with circular symbols. Performance $2\frac{1}{2}$ months post-operatively is shown using dark gray symbols. Performance $13\frac{1}{2}$ months post-operatively is shown using light gray symbols. (c) Performance for IF (one of two normal observers). Error bars are shown.

simultaneously for 500 ms, as shown in Fig. 13a. Both lines subtended 10.8° vertically and 1.5 min horizontally. The standard line was always positioned at the center of the screen and always had a contrast of 24% (a luminance of 123 cd/m^2). The second, test line could take one of 14 positions ranging between 3 and 45.4 min of visual angle to either the right or the left of the first line. The maximum possible contrast of the test line was 12%. The background luminance of the display was always 76 cd/m^2. Observers sat a viewing distance of 1 m in a dark room and the display was viewed monocularly with free fixation.

Observers were asked to report whether the test line was to the right or the left of the bright standard line, and were given auditory feedback. Observers were given as much time as they liked to respond. The luminance (and hence the contrast) of the test line was varied to find a threshold luminance for this task using a modified Quest procedure that converged on 84% correct.

6.2. Results and conclusions

Fig. 13b and c shows thresholds for PD and a normal observer (IF). As predicted, PD showed a distinct asymmetry in his ability to detect the test line. In the right eye PD's thresholds were higher when the test line was to the right of the standard. In the left eye (not shown) the reverse was true. Neither of the two normal observers showed this asymmetry in either eye. When the test line was close to the standard (within ±9.0 min for PD, within ±3.0 min for normal observers) performance did not reach threshold, even when the test line was 50% the contrast of the standard (the maximum possible contrast). When the two lines were close together they appeared to merge into a single thick line, making it impossible to judge whether the dimmer test line was to the left of the bright standard line. These points are not shown.

These data provide strong evidence for neural suppression of the pre-operative double images that PD reported. This neural compensation persisted for a considerable period post-operatively—these measurements were taken $2\frac{1}{2}$ months post-operatively, and further measurements taken $13\frac{1}{2}$ months later still demonstrated suppression. The phenomenal appearance of edges may have been mediated by the outputs of oriented edge detectors whose receptive fields were asymmetrically modified to compensate for his optics.

7. Experiment 6—letter acuity before and after cataract removal

We measured PD's letter acuity before and after cataract removal to determine whether he had visual deficits beyond simple deficits in visual resolution and sensitivity. In amblyopia, letter acuity tends to be worse than would be predicted by grating acuity: grating detection may be robust to certain visual deficits (such as positional jitter) associated with amblyopia (e.g. Friendly, Jaafar, & Morillo, 1990; Kushner, Lucchese, & Morton, 1995). We also measured PD's sensitivity to low-pass filtered letters, and crowded letters.

We also examined whether PD would show post-operative learning on the letter acuity task. Although PD showed only a small improvement in neural sensitivity function $2\frac{1}{2}$ months after his cataracts were removed and almost no improvement in his resolution limit 20 months post-operatively, we thought it possible that PD might nonetheless show some visual recovery on a letter identification task. Levi and Polat (1996) and Levi, Polat, and Hu (1997) have demonstrated small amounts of neural plasticity in adult amblyopes trained in letter identification and Vernier discrimination tasks.

7.1. Methods

Letters were presented at maximum contrast with abrupt onset. The letters were chosen randomly without replacement from the set of capitalized letters and numerals in the font Courier New. The point size of the letters varied between 9 and 48 points, and the viewing distance was 6 ft. The monitor was viewed binocularly in a darkened room and observers were free to scan the stimulus for as long as they wished before pressing the key corresponding to their guess as to what the character was. Letter size was adjusted using a staircase method on the basis of performance. Letter size was increased on an incorrect response and decreased on a correct response. Observers were given visual feedback immediately after each trial.

Three different conditions were tested. In the *individual Snellen* condition capitalized letters chosen randomly from the Snellen set {B, C, D, E, F, L, O, P, T, Z} were presented singly. In the *crowded Snellen* condition letters were chosen from the Snellen set and were presented in groups of three (Fig. 14a). The spacing between the letters in the crowded Snellen condition was approximately a third of the average letter width, well within the distance at which crowding effects are observable (Giaschi, Regan, Kraft, & Kothe, 1993). Observers memorized which letters were included in the Snellen set before the beginning of the experiment.

We also tested identification of low-pass filtered letters, in both individual and crowded Snellen conditions. In the *low blur* condition the low-pass filter was Gaussian with a half height of 5.7 cpd, and in the *high blur* condition the Gaussian filter had a half height of 3.4 cpd.

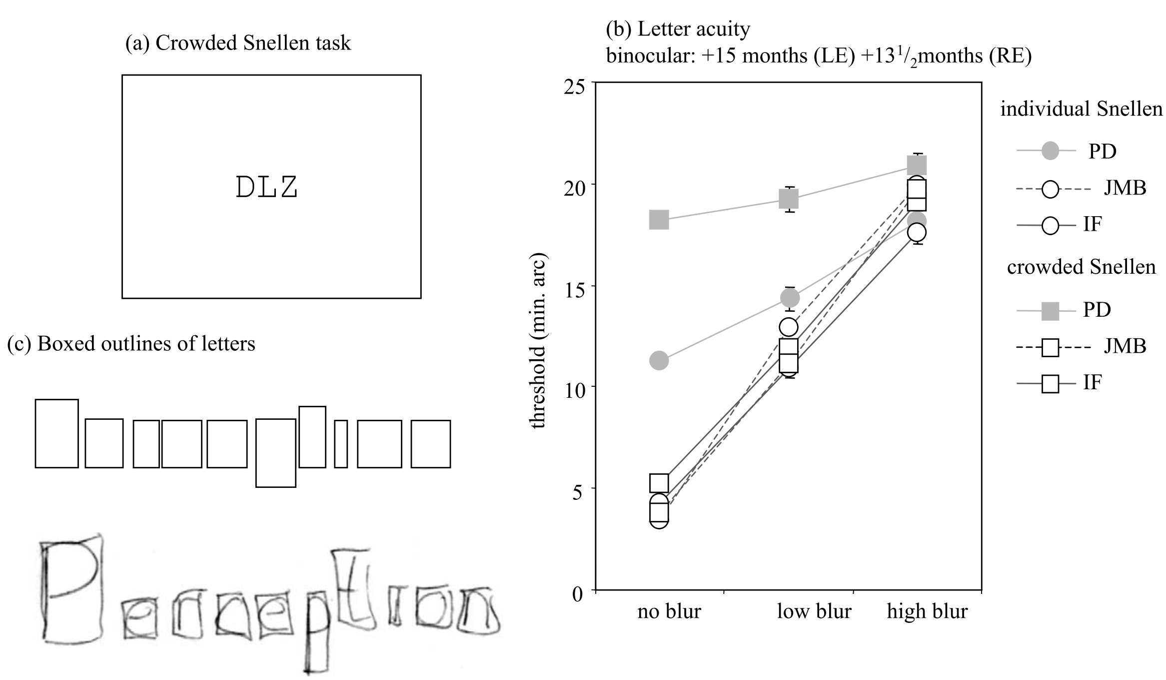

Fig. 14. (a) The stimulus used in the crowded Snellen condition. Observers were asked to identify all three letters. However only performance identifying the middle letter was used to calculate the threshold. (b) Performance in individual and crowded Snellen conditions, and unblurred, low blur and high blur conditions for PD and two normal observers. The individual Snellen condition is represented by circular symbols, the crowded Snellen condition by square symbols. PD—gray symbols, solid lines. JMB—empty symbols, dashed lines. IF—empty symbols, solid lines. Error bars are shown. (c) The boxed outline of a word, and a drawing by PD that includes the inferred letters.

To examine improvement with practice PD performed repeated sessions of the unblurred individual Snellen condition (2400 trials over 12 sessions) and the unblurred crowded Snellen condition (2600 trials over 13 sessions).

7.2. Results and conclusions

Fig. 14b shows performance in individual (circles) and crowded Snellen (squares) conditions for PD (dark gray, solid lines), IF (empty symbols, solid lines) and JMB (empty symbols, dashed lines). Both normal observers showed very similar performance. In the unblurred individual Snellen condition, PD could resolve letters vertically subtending 11.3 min of visual angle with 84% accuracy. In comparison, IF and JMB (normal observers) could resolve letters subtending 4.3 and 3.5 min of visual angle respectively. PD's threshold was therefore almost three times worse than normal observers (he showed performance slightly worse than predicted by his clinically measured post-operative visual acuity, which was between 20/40 and 20/50).

A "standard" observer with Snellen acuity of 20/20 can identify a letter subtending 5 min of visual angle, and has a resolution limit of 30 cpd. Such an observer recognizes letters when there are about 2.5 cycles/letter, consistent with Solomon and Pelli (1994)'s evidence that a 1–2 octave filter centered on 3 cycles/letter mediates letter recognition in normal observers. Assuming a normal resolution limit of 40 cpd, our normal observers had thresholds of 2.3–2.9 resolvable cycles/letter. According to PD's post-operative external resolution limit (which varied between 16 and 23 cpd depending on orientation), he was able to recognize letters when there were between 3 and 4.3 resolvable cycles/letter. PD therefore showed a deficit in letter identification that could not be fully explained by his low resolution limit.

Consistent with PD failing to use high spatial frequency information to recognize letters, PD's (gray symbols) acuity was much less affected by low-pass filtering the letters than normal observers, and under the high blur condition his performance matched normal observers. PD's thresholds for individual Snellen letters were raised by a factor of 1.27 in the low blur condition and by a factor of 1.61 in the high blur condition (Fig. 14b, gray circles). In comparison, in normal observers individual Snellen letter thresholds were elevated by a factor of 3 in the low blur condition, and by a factor of 4.85 in the high blur condition (Fig. 14b, empty circles, solid and dashed lines). As described above, PD compensated neurally for pre-operative optics by increasing the gain for high spatial frequencies. Despite this, PD relied on high spatial frequencies less heavily in letter identification than did normal observers, presumably because pre-operatively (regardless of compensatory gain) they had a low signal to noise ratio. When identifying letters PD reported that he relied heavily on the overall shape of letters and their position within words, rather than looking for individual features of letters. Consistent with this, he recalled noticing that it was relatively easy for him to infer letters from their boxed outlines. Fig. 14c shows the boxed outline of a word, and a drawing by PD including the inferred letters.

PD was more susceptible to crowding than normal observers. Adding flanking letters to the central test letter (the crowded Snellen condition, Fig. 14a) increased PD's threshold by a factor of 1.6. Normal observers did not show such strong evidence of crowding: thresholds for IF and JMB increased by a factor of 1.2 and 1.1 respectively between the individual and crowded Snellen conditions. A similar susceptibility to positional jitter and crowding effects has been noted in amblyopes (Flom, Weymouth, & Kahneman, 1963; Giaschi et al., 1993; Levi, 1991; Levi & Klein, 1985; Schapero, 1971; Simmers, Gray, McGraw, & Winn, 1999). The pre-operative optics of PD's eyes tended to distort his visual input, and produce blurred double images of high contrast lines, which may have also increased PD's susceptibility to crowding effects.

These crowding effects are the only neural consequence of the cataracts that we found that was pre-operatively maladaptive. All other differences between PD and normal observers could be explained in terms of PD making the most of limited and distorted visual input. Contrast constancy and suppression of double images only became maladaptive after PD's cataracts were removed. These crowding effects may be permanent, since PD showed almost no improvement in letter acuity more than a year post-operatively. Crowding effects in amblyopes are thought to be due to cortical changes (such as enlarged cortical receptive fields and undersampling) that may only be partially reversible in adulthood (Blakemore, Garey, & Vital-Durand, 1978; Kratz & Spear, 1976). In the case of normal observers there seemed to be little interaction between crowding and blur, whereas for PD there was an interaction between the two: the effects of blur were larger in the individual than in the crowded Snellen condition. This interaction is probably due to a type of ceiling effect. In the crowded blur conditions it may be crowding rather than blur that limits performance; the effects of crowding and blur seem not to be strictly additive.

We compared letter confusions made by PD with those made by normal observers identifying low-pass filtered letters, using the entire alphabet. PD confused certain pair of letters with a significantly higher probability than normal observers identifying low-pass filtered letters in a study by Loomis (1982) and Gilmore, Hersh, Caramazza, and Griffin (1979). Table 1 shows the letter confusions to which PD was more susceptible than normal observers, capitalized and in Courier New font, as in the experiment. The asterisks in the third column denote statistical significance ($^{**}p < 0.01$; $^{*}p < 0.05$). PD

Table 1
Letter confusions to which PD was more susceptible than normal observers

Letter presented	Letter chosen	p
R	B	**
K	E	**
S	E	**
N	L	**
Y	M	**
Y	O	**
Z	S	**
M	N	**
H	N	**
H	R	**
E	S	**
N	W	**
H	B	*
R	E	*
M	L	*
B	N	*
S	Z	*
L	X	*

$^{*}p < 0.05$; $^{**}p < 0.01$.

had particular difficulties identifying letters that were distinguished by containing vertical or oblique lines, and had trouble distinguishing oblique lines from vertical lines. This is consistent with his lower sensitivity to vertical than horizontal lines (Fig. 4). Even post-operatively, letter stimuli that were near his resolution threshold seemed to be susceptible to perceptual instability, oscillating between possible letters (see below).

Finally, we examined PD's performance on the letter recognition task as a function of time post-operatively. PD showed small improvements in his letter acuity in the first few post-operative days. After the first few days there was almost no improvement in PD's letter acuity threshold, despite his spending a large amount of time reading, and carrying out many thousands of trials of letter discrimination practice over several months.

8. Discussion

PD's visual experience provides an insight into the extent to which the good match between the human visual system and the visual environment is due to developmental plasticity. There is strong neurophysiological evidence for the existence of a critical period during visual development in animals (Wiesel & Hubel, 1965a,b). However there is also evidence for at least a limited amount of cortical plasticity in both adult animals (Recanzone, Merzenich, Jenkins, Grajski, & Dinse, 1992) and adult humans (Levi & Polat, 1996; Levi et al., 1997). Previous studies of sight recovery after extended periods of blindness have found weak correlations between success in using post-operative vision and the age at which patients became blind, the length of time they had been blind, and the amount of residual vision (Wright et al., 1992). Though the post-operative visual performance of patients who have been blind since early childhood seemed to improve over time, most continued to have extreme difficulties using their sight functionally (Ackroyd et al., 1974; Gregory & Wallace, 1963; Sacks, 1993; Valvo, 1971). However in most of these cases patients had suffered much more severe visual deprivation than PD, and their visual systems are likely to have been grossly abnormal.

In contrast, the experiments in this paper address the question of how the visual system adjusts to limited and distorted visual input, rather than full deprivation. PD's neural adaptation to his cataracts probably began sometime between 13 months (when his cataracts were not yet easily observable) and 21 months (when his cataracts were first noticed). The wide range of adaptations that we observed, listed in the first column of Table 2, suggests that even the earliest levels of visual processing can adapt themselves to the peculiarities of an individual's visual environment. Once PD's cataracts were removed as an adult he demonstrated a certain amount of readaptation to his newly improved visual input, as listed in the second column of Table 2.

Table 2
Pre- and post-operative adaptations to limited visual deprivation

Pre-operative adaptation	Post-operative adaptation
Photoreceptors aligned towards the temporal margins of the pupil.	Photoreceptors realigned towards the pupil over a time period of 10 days (Fig. 11c).
Neural CSF fell off at high spatial frequencies more sharply than normal observers.	Almost no improvement in neural sensitivity post-operatively (Fig. 3).
Retinally blurred edges appeared sharp pre-operatively: the gain of neural contrast compensation matched pre-operative optics. Post-operative "overcompensation": sharp edges appeared scalloped, and the contrast of high spatial frequencies was overestimated.	Reduction in neural overcompensation over more than a year (Fig. 10), for both square waves and contrast matching.
Retinal double images (the result of a combination of annular clear regions of pupil and hyperopia) neurally suppressed.	Small reduction in suppression over more than a year (Fig. 13b).
Letter acuity poorer than predicted by grating acuity.	After the first few days of practice there was no improvement in letter acuity, despite thousands of trials.

However in general plasticity as an adult seemed to be very slow and/or limited.

Post-operatively, PD made many qualitative observations about his post-operative vision. As with previous cases of cataract removal (Davenport & Foley, 1979), color was one of the first things PD noticed after surgery: "*My daughter's dark red sweater was probably the first thing I noticed, and it was... very colorful, more colorful than I was used to,... with one eye done, I could constantly compare what it was like to see color... with the good new eye versus the old bad eye, and it was quite striking. In fact, it made me kind of angry that people were walking around in this colorful world that I had never had access to, but I am happy to say that I am now part of this, I can now look at all these colors without particularly appreciating them just like anybody else*". Pre-operatively PD suffered from severe light scatter, which reduced the saturation and intensity of colors on his retina. Pre-operatively, PD was not aware of his world being desaturated, as he commented in the context of this and other visual deficits, "*if you do not have it* [*a visual ability*], *you do not know you do not have it*". His post-operative oversaturation may have been due to chromatic signals being neurally "boosted", similarly to the way in which the apparent contrast of high spatial frequencies was boosted, i.e. chromatic analogs to his "oversharpening" of edges. Normal observers adapted to long wave light also see green stimuli as being supersaturated (DeValois & Walraven, 1967; Helmholtz, 1867). However supersaturation as a result of adaptation only lasts for minutes, whereas PD reported that colors seemed intense for several weeks post-operatively. The gradual reduction in the apparent intensity of colors may have been due to similar neural processes as those mediating the slow adjustment to apparent contrast.

Pre- and post-operatively PD seemed to be more susceptible to perceptual instability than normal observers, and this perceptual instability seemed to apply to tasks, such as letter recognition, that normally produce very stable percepts. When trying to identify letters at the limit of his resolution he reported features "*jiggling back and forth*" or "*hopping into view*". In some cases these features seemed to exist independently of the main image of the letter, "*I will get a sensation of the curve of the 'p' sort of appearing somehow. It is hard to say where... maybe somewhat superimposed on the figure*". The features might then appear to boil around without well-defined and stable spatial relationships, forming a "*feature soup*". The greater susceptibility to crowding effects in PD and in other amblyopes has been explained in terms of spatial uncertainty in the localization of detected features, as if the feature-detector arrays available are too sparse to match the precision of the optical input (Hess, Campbell, & Greenhalgh, 1978; Levi & Klein, 1985). Like normal observers with the bistable rabbit–duck illusion or the Necker cube, PD often seemed to oscillate between two (or more) convincing percepts. "*The prong of an 'e' coming out... or the tail of a 'q', it will just sort of pop out and then go back, like a lizard flicking out its tongue. And it seems real, it is like the lizard's tongue, it was here briefly and it is gone... but it certainly seems real*".

Finally, PD noted that seeing people's faces more clearly after surgery was rather disquieting for a number of reasons ("*A lot of people have gotten pimples recently*"). People showed more emotion on their faces than he had realized: for a long time post-operatively it seemed impolite to look at someone's face, "*People live closer to each other than I had realized... I am not used to the idea that I can tell so much about them by looking, it is not something I am used too... whereas... the colors, okay, I am used to it, I am blasé, but other aspects, I am just not used to yet.*"

Understanding the effects of long-term visual deprivation, and the limits of adult visual plasticity will have growing medical relevance, given the recent advances in sight restoration procedures (Dobelle, 2000; Tsubota et al., 1999). Currently many adult sight restoration patients are post-operatively limited by the ability of their post-retinal visual system to make good use of unfamiliar input. Fortunately for PD, despite remaining neural limitations, his operation was a success. "*It is bizarre to drive a car with no one else in it... I can see that now is the time when regret over missed opportunities is most likely to set in... As it starts to sink in that at last I have all the freedom of a 16-year old, I think it would be very easy to feel regret over the well-nigh 30 years of my extended dependency. Taking a more positive view, most people my age are blasé about driving, and maybe about life in general, whereas I have the opportunity to savor one of the sweetest joys of adolescence. O, brave new world that has such vehicles in't!*"

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